Renewable and Sustainable Energy Reviews 15 (2011) 905–915

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Offshore wind power development in Europe and its comparison with onshore counterpart

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ARTICLE INFO

Article history:
Received 4 August 2010
Accepted 4 November 2010

Keywords:
Onshore wind energy
Offshore wind energy
Wind power
Renewable energy
Wind

ABSTRACT

Wind power, as a renewable source of energy, produces no emissions and is an excellent alternative in environmental terms to conventional electricity production based on fuels such as oil, coal or natural gas. At present, the vast majority of wind power is generated from onshore wind farms. However, their growth is limited by the lack of inexpensive land near major population centers and the visual pollution caused by large wind turbines. Comparing with onshore wind power, offshore winds tend to flow at higher speeds than onshore winds, thus it allows turbines to produce more electricity. Estimates predict a huge increase in wind energy development over the next 20 years. Much of this development will be offshore wind energy. This implies that great investment will be done in offshore wind farms over the next decades. For this reason, offshore wind farms promise to become an important source of energy in the near future. In this study, history, current status, investment cost, employment, industry and installation of offshore wind energy in Europe are investigated in detail, and also compared to its onshore counterpart.

Contents

1. Introduction

Wind is air in motion. Since the earth's surface is made of various land and water formations, it absorbs the sun's radiation unevenly. Wind is produced by the uneven heating of the earth's surface by the sun [1]. A wind energy system transforms the kinetic energy of the wind into mechanical or electrical energy that can be harnessed for practical use. Mechanical energy is most commonly used for pumping water. Furthermore, it can also be used for many other purposes such as grinding grain, sawing, pushing a sailboat, etc. Wind electric turbines generate electricity for homes and businesses and for sale to utilities [2]. Wind energy can be deployed rapidly, as turbines and wind plants are quick to install. It is the cheapest way of renewable energy, which encourages investment. It also creates benefits in terms of employment, investment, research, economic activity and energy independence in the electricity sector [3].

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2010.11.006

Furthermore, it is well known that wind energy is one of the cleanest and most environmentally friendly energy sources, and unlike fossil fuels, the wind will never be depleted. All forms of energy production have an environmental impact, but the impacts of wind energy are low, local, and manageable. These environmental impacts are negligible when compared with conventional energy sources. The significance of wind energy originates from its friendly behavior to the environment. Due to its clean, wind power is sought wherever possible for conversion to electricity with the hope that air pollution from fossil fuels will be reduced [4].

There are different alternatives for wind energy such as onshore and offshore. Onshore, wind energy has been utilized for power generation for more than two thousand years. On the other hand, the history of offshore wind power generation is fairly recent. In recent years, the wind power sector has begun to move offshore, i.e. to use space and good wind speeds on the open sea for large scale electricity generation [5]. Offshore wind farms are constructed in general on the continental shelf area which is about 10 km away from the coast and 10 m deep. Compared with land, offshore wind turbines must be fixed on the seabed, which demand a more solid supporting structure. Submarine cables are needed for transmission of electricity, and special vessels and equipments are required for building and maintenance work. These factors create high costs, with double or triple the cost on land [6].

Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise can be mitigated by distance. Because water has less surface roughness than land (especially deeper water), the average wind speed is usually considerably higher over open water. Capacity factors are considerably higher than for onshore and nearshore locations which allow offshore turbines to use shorter towers, making them less visible. In addition, installing wind turbines offshore has several advantages over onshore development. Onshore, difficulties in transporting large components and opposition due to various siting issues, such as visual and noise impacts, can limit the number of acceptable locations for wind farms. Offshore locations can take advantage of the high capacity of marine shipping and handling equipment, which far exceeds the lifting requirements for multi-megawatt wind turbines. On land, larger wind farms tend to be in somewhat remote areas, so electricity must be transmitted over long power lines to cities. Offshore wind farms can be closer to coastal cities and require relatively shorter transmission lines, yet they are far enough away to reduce visual and noise impacts [7].

Offshore wind farms make new technological demands on the wind power industry not only with respect to the development of the wind turbines themselves and with their connection to the electricity grid but also with respect to the logistics of transport, installation, operation and maintenance. This has led to the need for a new combination of research areas [8]. In this study, history, current status, technical potential area, investment cost, employment, industry and installation of offshore wind energy in Europe are investigated in detail, and also compared to its onshore counterpart.

2. Advantages and disadvantages

There are many advantages of offshore wind energy, compared to its onshore counterpart. Offshore wind power is more complex and costly to install and maintain but also has several key advantages. Winds are typically stronger and more stable at sea, resulting in significantly higher production per unit installed. Wind turbines can also be bigger than on land because it is easier to transport very large turbine components by sea. Installing wind turbines sufficiently far from the shore can nearly eliminate the issues of visual impact and noise. This makes it possible to use different designs for the turbines, improving their efficiency. This also makes huge areas available for the installation of large wind farms. As transportation and erection are made at sea, there is virtually no limit on the size of the turbines that can be installed, as opposed to limits imposed by road restrictions onshore. Also, offshore wind farms can be installed close to major urban centers, requiring shorter transmission lines to bring this clean energy to these high energy cost markets [9]. Advantages of offshore wind power can be summarized as [10]:

- availability of large continuous areas, suitable for major projects,
- elimination of the issues of visual impact and noise,
- higher wind speeds, which generally increase with distance from the shore,
- less turbulence, which allows the turbines to harvest the energy more effectively and reduces the fatigue loads on the turbine,
- lower wind-shear, thus allowing the use of shorter towers.

But against this is the very important disadvantage of the additional necessary capital investment, relating to:

- the more expensive marine foundations,
- the more expensive integration in to the electrical network and in some cases a necessary increase in the capacity of weak coastal grids,
- the more expensive installation procedures and restricted access during construction due to weather conditions,
- limited access for operations and maintenance during operation.

3. History and development

3.1. Onshore

The wind has played a long and important role in the history of human civilization. Since earliest recorded history, wind power has been used to move ships, grind grain and pump water. There is evidence that wind energy was used to propel boats along the Nile River as early as 5000 B.C. The western world discovered wind power much later. The earliest written references to working wind machines date from the 12th century. These were used for milling grain. Windmill performance was continuously improved between the 12th and 19th centuries. By the end of the 19th century, the typical European windmill used a rotor of 25 m in diameter and the stocks reached to 30 m. The first person, who generated in 1891 electricity from wind speed, was the Dane Poul LaCour, who lived in Denmark. The popularity of using the energy in the wind has always fluctuated with the price of fossil fuels. When fuel prices fell after World War II, interest in wind turbines disappeared. With the oil crises in the beginning of the 1970s, interest in wind power generation resumed [4,11,12].

The wind technology has improved step by step since the early 1970s. Before the 1980s, a number of experimental turbines had been erected, but there were no commercial wind farms and no industry to manufacture the hardware. In the 1980s, the first wind farms were built in California [3]. By the end of the 1990s, wind energy has re-emerged as one of the most important sustainable energy resources. Today, it is the leading source of renewable electricity, and it becomes an international business sector, spreading beyond its original markets in a few European countries, India and the United States. The major manufacturers and project developers now operate across five continents. Over 80 countries around the world now contribute to the global total [13].

3.2. Offshore

The first thoughts of locating wind turbines offshore came immediately after 1930 when it was suggested that wind turbines be placed on pylons. Although these suggestions were never used, they made a promising start and in 1972, approximately 40 years after the original idea, Dr. William E. Heronemus, professor at M.I.T. University introduced the idea of large floating wind turbine platforms in order to produce electrical energy. In 1990, 18 years after the time that professor William E. Heronemus first had his vision for the construction of floating wind turbines, a company called 'World Wind' constructed and installed the first offshore wind turbine at sea. This offshore wind turbine was located in Nogersund, 250 m offshore, in 7 m water depth off the North part of Sweden and had a rated power of 220 kW [14].

Development of offshore wind power in the EU between the years 1991 and 2008 is presented in Fig. 1 [15]. Operational offshore wind farms in the EU are given in Table 1 [15]. In 1991, at Vindeby in Denmark and at a distance of 2.5 km offshore, the first large commercial offshore wind farm was constructed, having a rated power of 4.95 MW and consisted of 11 Bonus wind turbines of 450 kW each. The water depths at that site are from 2.5 to 5 m and the annual energy production is equal to 12 GWh/year. In 1995, Denmark constructed its second offshore wind farm at Tuno Knob. This offshore wind farm has a power output of 5 MW and consists 10 Vestas wind turbines of 500 kW placed at water depths between 0.8 and 4 m and the annual energy production is equal to 16 GWh/year [14]. The next Danish offshore wind farm was constructed in the port of Copenhagen. Basically, this was the first large offshore wind farm with a rated power of 40 MW. It includes 20 Bonus wind turbines of 2 MW each that are placed at a distance of 3 km offshore and at a water depth of between 5 and 10 m. Middelgruden, as it is called, had a total cost of 54 million Euros and construction ended in 2000. In 2002, Horns Rev offshore wind farm, which is the largest offshore wind farm up till now, was constructed with a total power production of 160 MW. It includes 80 Vestas wind turbines of 2 MW each that are located at a distance between 14 and 17 km offshore and at water depths between 6 and 14 m. In 2003, the next three offshore wind farms were constructed in Denmark. The first one is Frederikshavn with a rated power of 10.6 MW and includes 4 Bonus wind turbines of 2.65 MW each. The second one is Samso island with a total electrical production power of 23 MW. It includes 10 Bonus wind turbines of 2.3 MW which are placed at water depths of 20 m offshore, 3.5 km offshore. The last one is Nysted offshore wind farm with a total electrical production power of 165.6 MW [14].

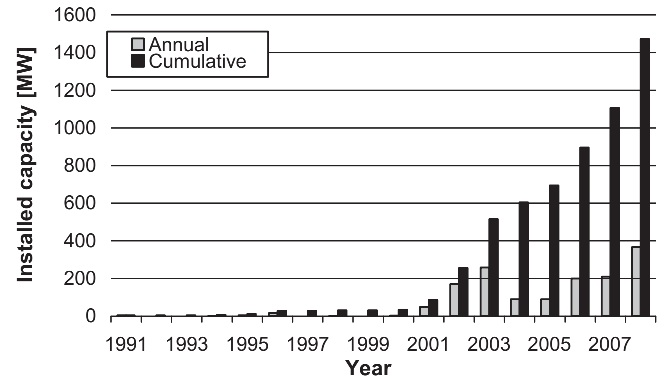

Fig. 1. Development of offshore wind power in the EU between.

Netherlands is the country that developed offshore wind farms immediately after Denmark. In 1994 at a site called Lely, the first sea environment wind farm for Netherlands was constructed at water

Table 1
Operational offshore wind farms in the EU.

No	Project, location	Capacity (MW)	Number of turbines	Water depth (m)	Distance to shore (km)	Year of installation	Wind turbine manufacturer
1	Vindeby, Denmark	4.95	11	2.5–5	2.5	1991	Bonus
2	Lely, Netherlands	2	4	7.5	0.75	1994	Nedwind
3	Tunø Knob, Denmark	5	10	0.8–4	6	1995	Vestas
4	Irene Vorrink, Netherlands	16.8	28	2	0.03	1996	NordTank
5	Bockstigen, Sweden	2.8	5	6–8	3	1998	Winworld
6	Blyth, United Kingdom	3.8	2	6	1	2000	Vestas
7	Middelgrunden, Denmark	40	20	5–10	2–3	2001	Bonus
8	Utgrunden I, Sweden	10.5	7	4–10	7	2001	GE
9	Horns Rev 1, Denmark	160	80	6–14	14–17	2002	Vestas
10	Yttre Stengrund, Sweden	10	5	8–12	4	2002	NEG-Micon
11	Nysted, Denmark	165.6	72	6–10	6–10	2003	Siemens
12	Samsø, Denmark	23	10	11–18	3.5	2003	Bonus
13	Frederikshavn, Denmark	10.6	4	3	0.8	2003	Vestas, Bonus, Nordex
14	North Hoyle, United Kingdom	60	30	5–12	7.5	2003	Vestas
15	EndemEms, Germany	4.5	1	–	<1	2004	Enercon
16	Arklow Bank, Ireland	25.2	7	15	10	2004	GE
17	Scroby Sands, United Kingdom	60	30	2–10	3	2004	Vestas
18	Kentish flats, United Kingdom	90	30	5	8.5	2005	Vestas
19	Breitling, Germany	2.5	1	2	1	2006	Nordex
20	Egmong ann Zee, Netherlands	108	36	17–23	8–12	2006	Vestas
21	Barrow, United Kingdom	90	30	15	7	2006	Vestas
22	Lillgrund, Sweden	110	48	2.5–9	10	2007	Siemens
23	Beatrice, United Kingdom	10	2	40	25	2007	Repower
24	Burbo Bank, United Kingdom	90	25	10	5.2	2007	Siemens
25	Thornton Bank phase 1, Belgium	30	6	12–27	27–30	2008	Repower
26	Kemi Ajos phases 1 + 2, Finland	24	8	–	<1	2008	–
27	Hooksiel, Germany	5	1	2–8	0.4	2008	Enercon
28	Birindisi, Italy	0.08	1	108	20	2008	Blue H
29	Prinses Amalia, Netherlands	120	60	19–24	23	2008	Vestas
30	Inner Dowsing, United Kingdom	90	30	10	5.2	2008	Siemens
31	Lynn, United Kingdom	97	30	10	5.2	2008	Siemens
	Total	1471.33					

depths between 5 and 10 m with a rated power of 2 MW, and consisting of four 500 kW Nedwind wind turbines. Two years following the end of the construction of Lely's wind farm in a region called Irene Vorrink in the same lake, the second wind farm of 16.8 MW was constructed. 28 Nordtank 600 kW wind turbines were used for this site. The next two offshore wind farms were constructed in the Netherlands. The first one is Egmong Ann Zee offshore wind farm with a rated power of 108 MW and includes 36 Vestas wind turbines of 3 MW each. It was constructed in 2006. The second one is Prinses Amalia offshore wind farm with a total power production of 120 MW. It includes 60 Vestas wind turbines of 2 MW each that are located at a distance of 23 km offshore and at water depths between 19 and 24 m.

The first step towards harnessing offshore wind energy was taken in Sweden. Eight years after the first installation in Swedish waters and in 1998 at Bockstigen site, north of Gotland island, 5 Wind World wind turbines were installed with a rated power of 550 kW each. These wind turbines were installed at a distance of 3 km offshore at a water depth of 6 m. By 2001 and 2002, two new offshore wind farms were constructed in Sweden. The first one is Utgrunden and is situated between Oland Island and the shore. It uses 7 Enron wind turbines at a rated power of 1.425 MW each, which are placed 7 km offshore at water depths from 4 to 10 m. The second one is Yttre Stengrund, north of the island of Oland and includes 5 NEG-Micon Wind turbines of 1.425 MW each at a distance of 4 km offshore and at water depths from 8 to 12 m deep. In 2007, Lillgrund offshore wind farm was constructed with a total power production of 110 MW [14].

The first offshore wind farm for Ireland was constructed in 2004. It includes 7 GE wind turbines of 3.6 MW each, which are located at a distance of 10 km offshore at water depths between 5 and 25 m.

Germany has the largest share of planned capacity, but has no significant operational wind farms, yet. The first German offshore wind farm Alpha Ventus is under construction 45 km North of the North Sea island of Bochum. In total, there are 40 approved offshore wind farms with 20,000 MW of planned capacity, 81% of which is in German waters [7,16].

Great Britain joined the leading group of countries that test offshore wind energy and by the year 2000, the first wind farm has been constructed in an area called Blyth in south-west England with a rated power of 3.8 MW. This farm includes 2 Vestas wind turbines of 1.9 MW each that are placed at a distance of 800 m offshore at a water depth of between 6 and 11 m. Great Britain constructed North Hoyle, its second offshore wind farm, 7.5 km offshore from North Wales. It includes 30 Vestas wind turbines of 2 MW at water depths of 5–12 m. Scroby Sands wind farm (60 MW) was constructed in 2004 followed by Kentish Flats (90 MW) in 2005, Barrow (90 MW) in 2006. In 2007, Beatrice offshore wind farm, which is the deepest offshore wind farm constructed to date, was constructed with a total power production of 10 MW.

Offshore wind development in France is slow, as there is no specific legislative or administrative framework for the development of offshore wind energy, and the framework applying to offshore economic activity is not adapted to wind energy. Preparation for the first offshore wind farm in France began with a government tender in 2005, but due to long authorization procedures, construction has been delayed and is now scheduled to start in 2009 or 2010. However, there are indications that the principle of exclusion zones will no longer be applicable offshore, and work has begun on simplifying offshore planning procedures [17].

4. Current status

4.1. Global wind power

Wind energy is the world's fastest-growing energy. Both in Europe and worldwide, wind power is being developed rapidly. In 2008, more wind power capacity was installed in the EU-27 than any other electricity generating technology, as seen from Fig. 2. A total of 8484 MW wind power capacity was installed in the EU-27. This puts wind energy ahead of any other power technology for the first time. 36% of all new electricity producing capacity installed in the EU was wind energy followed by natural gas (6932 MW – 29%), photovoltaic (4200 MW – 18%), oil (2495 MW – 10%), coal (762 MW – 3%) and hydro (473 MW – 2%). At the end of 2008, there were 65 GW of wind power capacity installed in the EU-27 producing 142 TWh hours of electricity, equal to about 4.2% of the EU's electricity demand, and avoid the emission of 108 million tonnes of CO_2 per year, the equivalent of taking more than 50 million cars off Europe's roads. On average, 20 wind turbines were installed for every working day of 2008. By the end of the year 2008, 160,000 workers were employed directly and indirectly in the sector, which saw investments of about €11 billion in the EU [18,19].

Wind energy has become an important player in the world's energy markets, with the 2008 market for turbine installations worth about €36.5 billion. The wind industry also creates many new jobs; over 400,000 people are now employed in this industry, and that number is expected to be in the millions in the near future. The wind now generates more than 1.5% of the world's electricity, up from 0.1% in 1997. Around the world, 80 countries are now using wind power on a commercial basis [17,20].

Fig. 3 shows the cumulative installed wind power capacity in the world and Europe between 1990 and 2008 [17,21]. There is an increasing trend in installed wind energy over this period. In 1990, there was only 1743 MW of wind power capacity installed in the world. On the other hand, 2008 was a record breaking year for the

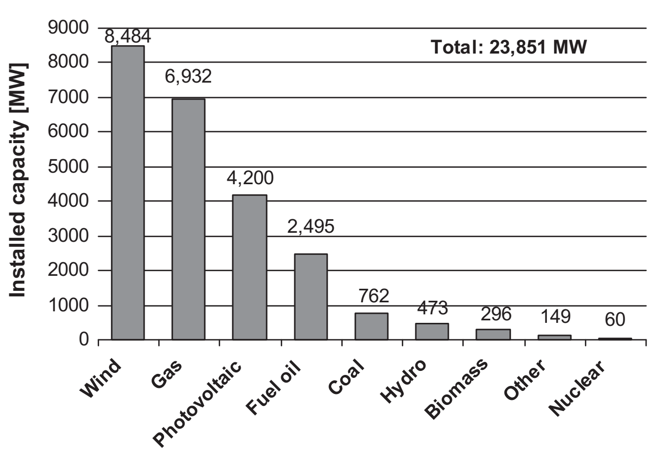

Fig. 2. The EU's new power capacity installed in 2008.

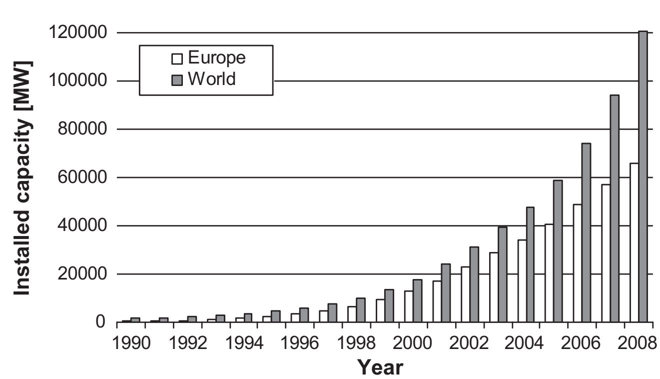

Fig. 3. Cumulative installed wind power capacity.

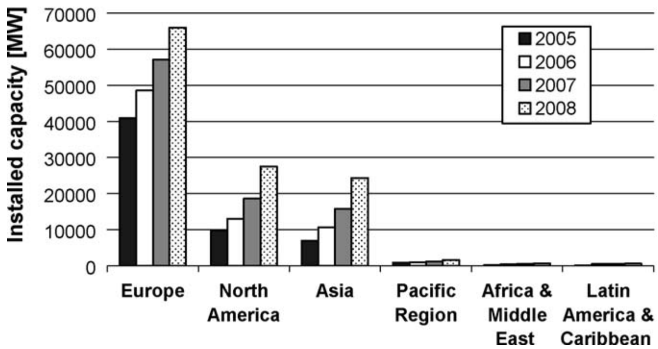

Fig. 4. Cumulative installed wind power capacity by region.

wind industry. 27,051 MW of wind power was installed in 2008, led by the US, China, India, Germany and Spain, bringing worldwide installed capacity to 120,798 MW. This is an increase of 36% compared with the 2007 market, and represents an overall increase in global installed capacity of about 29%.

The cumulative installed wind power capacity by region is presented in Fig. 4 [17]. It can be seen here that Europe is the global leader in the wind energy sector. Europe decreased its share in total installed capacity from 66% in 2006 to 61% in the year 2007 further down to 55% in 2008. However, Europe is still the strongest continent while North America and Asia are increasing rapidly their shares. Approximately 55% of the total installed wind capacity of the world is in Europe, 23% in America and 20% in Asia. In the European Union (EU), installed wind power capacity has increased by an average of 27% annually over the past 10 years, from 6453 MW in 1998 to 65,933 MW in 2008.

The cumulative installed wind electricity-generating capacity in leading countries and the world between the years 1980 and 2008 is given in Table 2 [21]. As seen from the table that the United States, which launched the modern wind power industry in California in the early 1980s, leads the world with 25,170 MW. Germany follows with 23,903 MW. Spain is in third place, with 16,754 MW. PR China, which is fourth with 12,210 MW, is the leader of the wind energy sector in Asia. India (9645 MW), Italy (3736 MW), France (3404 MW), the UK (3241 MW) and Denmark (3180 MW) are the other largest markets of the world.

4.2. Offshore

Offshore wind energy began in shallow waters of the North Sea where the abundance of sites and higher wind resources are more favorable by comparison with Europe's land-based alternatives. The first installation was in Sweden with a single 300-KW turbine in 1990 and the industry has grown slowly over the past 15 years [22]. Offshore wind currently accounts for a small amount of the total installed wind power capacity in the world. Fig. 5 shows a map of the operational offshore wind farms in North West Europe. Nine countries have operating offshore wind farms: Belgium, Denmark, Finland, Germany, Ireland, Italy, the Netherlands, Sweden and the UK, as seen in Table 3. By the end of 2008, 1473 MW of wind turbines were in operation offshore, more than 99% of it in Europe, representing slightly more than 1% of the total installed wind turbine capacity. 366 MW were added offshore in 2008 (compared to 8111 MW onshore), equalling a growth rate of 30%. The development of offshore wind has mainly been in northern European counties, around the North Sea and the Baltic Sea [23].

The UK installed more than any other country during 2008 and became the nation with the largest installed offshore capacity, overtaking Denmark. Activity in 2008 was dominated by ongoing work at Lynn and Inner Dowsing wind farms in the UK and by Princess Amalia in the Netherlands. In addition to these large projects, Phase 1 of Thornton Bank in Belgium was developed together with two nearshore projects, one in Finland and one in Germany. In addition, 80 kW turbine (not connected to the grid) was piloted on a floating platform in a water depth of 108 m in Italy. This turbine was the first to take the offshore wind industry into the Mediterranean Sea, which, together with developments in the Baltic Sea, North Sea and Irish Sea, highlights the pan-European nature of today's offshore wind industry [24]. At the end of 2008, offshore wind farm installations represented nearly 2.23% of the EU's total installed wind power capacity. Most of the capacity has been installed in relatively shallow waters (less than 10 m water depth), in order to minimize the extra costs of foundations and sea cables [23]. As seen from Fig. 6, the UK is now the world leader in offshore wind energy, with 590.8 MW installed capacity.

Significant offshore resources to be exploited in the near future have been identified in Finland, Ireland, Italy, the Netherlands, Norway, and Spain [7]. At present, the total capacity is limited, but growth rates are high. Several projects will be developed within

Fig. 5. A map of the operational offshore wind farms in North West Europe.

Table 2
Cumulative installed wind electricity-generating capacity in leading countries and the world, 1980–2008.

Year	U.S.	Germany	Spain	China	India	Italy	France	U.K.	Denmark	World
1990	1484	62	0	n.a.	0	0	0	0	343	1930
1991	1709	112	5	n.a.	39	0	0	4	413	2170
1992	1680	180	50	n.a.	39	2	0	69	458	2510
1993	1635	335	60	n.a.	79	4	2	n.a.	487	2990
1994	1663	643	70	n.a.	185	16	n.a.	n.a.	539	3490
1995	1612	1130	140	38	576	32	3	200	637	4780
1996	1614	1548	230	79	820	70	6	273	835	6100
1997	1611	2080	512	170	940	103	10	319	1120	7600
1998	1837	2870	830	224	1015	180	19	333	1428	10,200
1999	2490	4445	1584	268	1077	227	25	362	1718	13,600
2000	2578	6104	2235	346	1220	427	30	406	2300	17,400
2001	4275	8754	3337	402	1456	690	93	474	2417	23,900
2002	4685	11,994	4825	469	1702	797	148	552	2880	31,100
2003	6372	14,609	6203	567	2125	913	253	648	3110	39,431
2004	6725	16,629	8263	764	3000	1255	390	888	3117	47,620
2005	9149	18,415	10,027	1260	4430	1718	757	1353	3128	59,091
2006	11,575	20,622	11,623	2599	6270	2123	1567	1962	3136	74,052
2007	16,824	22,247	15,145	5910	7845	2726	2454	2406	3125	93,835
2008	25,170	23,903	16,754	12,210	9645	3736	3404	3241	3180	12,0798

n.a.: data not available.

Table 3
Cumulative installed offshore wind electricity-generating capacity in the EU, 1991–2008.

Year	The UK	Denmark	Netherlands	Sweden	Belgium	Ireland	Finland	Germany	Italy	Total
1991	0	4.95	0	0	0	0	0	0	0	4.95
1992	0	4.95	0	0	0	0	0	0	0	4.95
1993	0	4.95	0	0	0	0	0	0	0	4.95
1994	0	4.95	2	0	0	0	0	0	0	6.95
1995	0	9.95	2	0	0	0	0	0	0	11.95
1996	0	9.95	18.8	0	0	0	0	0	0	28.75
1997	0	9.95	18.8	0	0	0	0	0	0	28.75
1998	0	9.95	18.8	2.8	0	0	0	0	0	31.55
1999	0	9.95	18.8	2.8	0	0	0	0	0	31.55
2000	3.8	9.95	18.8	2.8	0	0	0	0	0	35.35
2001	3.8	49.95	18.8	13.3	0	0	0	0	0	85.85
2002	3.8	209.95	18.8	23.3	0	0	0	0	0	255.85
2003	63.8	409.15	18.8	23.3	0	0	0	0	0	515.05
2004	123.8	409.15	18.8	23.3	0	25.2	0	4.5	0	604.75
2005	213.8	409.15	18.8	23.3	0	25.2	0	4.5	0	694.75
2006	303.8	409.15	126.8	23.3	0	25.2	0	7	0	895.25
2007	403.8	409.15	126.8	133.3	0	25.2	0	7	0	1105.25
2008	590.8	409.15	246.8	133.3	30	25.2	24	12	0.08	1471.33

the coming years. 2009 has seen strong market development with a much larger number of projects beginning construction, under construction, expected to be completed, or completed during the course of the year. European Wind Energy Association (EWEA) anticipates an annual market in 2009 of approximately 420 MW, including the first large-scale floating prototype off the coast of Norway. By the end of 2009, EWEA expects a total installed offshore capacity of just under 2000 MW in Europe [24].

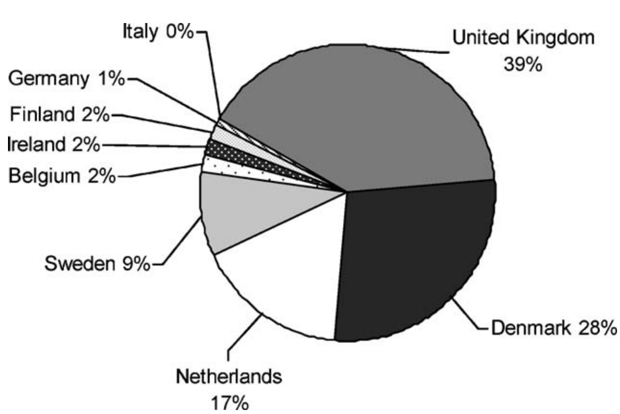

Fig. 6. Current status of offshore wind power in the EU.

Assuming the financial crisis does not blow the offshore wind industry off course, 2010 will be a defining year for the offshore wind power market in Europe. Over 1000 MW (1 GW) is expected to be installed. Depending on the amount of wind power installed onshore, it looks as if Europe's 2010 offshore market could make up approximately 10% of Europe's total annual wind market, making the offshore industry a significant mainstream energy player in its own right [24]. Prospects for 2015 look bright, with a total of more than 37 GW planned, as seen in Table 4. One critical element for an acceleration of the development of offshore wind energy in the EU is the rapid publication of the Commission's blueprint for a North Sea grid, the Baltic interconnection plan, and the Mediterranean ring [7].

5. Investment cost

5.1. Onshore

Table 5 [23] shows the typical cost structure for a 2 MW turbine erected in Europe. The average turbine installed in Europe has a total investment cost of around €1.23 million/MW. The turbine's

Table 4
Offshore wind power planned for 2015.

Country	Total installed by end 2015 (MW)	Total installed by end 2015 (%)
Belgium	1446	4
Denmark	1276	3
Finland	1330	4
France	1070	3
Germany	10,927.5	30
Ireland	1603.2	2
Italy	827.08	2
The Netherlands	2833.8	8
Norway	1553.8	4
Poland	533	1
Spain	1976.4	5
Sweden	3312	9
The United Kingdom	8755.8	23
Total	37,441.83	100

Table 5
Cost structure of a typical 2 MW wind turbine installed in Europe (€ 2006) [23].

	Investment (€1000/MW)	Share of total cost (%)
Turbine (ex works)	928	75.6
Grid connection	109	8.9
Foundation	80	6.5
Land rent	48	3.9
Electric installation	18	1.5
Consultancy	15	1.2
Financial costs	15	1.2
Road construction	11	0.9
Control systems	4	0.3
Total	1227	100

share of the total cost is, on average, around 76%, while grid connection accounts for around 9% and foundation for around 7%. The cost of acquiring a turbine site (on land) varies significantly between projects. Other cost components, such as control systems and land, account for only a minor share of total costs [23].

5.2. *Offshore*

Fig. 7 shows the expected annual wind power investments from 2000 to 2030 in the EU [23]. The market is expected to be stable at around €10 billion/year up to 2015, with a gradually increasing share of investments going to offshore. By 2020, the annual market for wind power capacity will have grown to €17 billion annually with approximately half of investments going to offshore. By 2030, annual wind energy investments in EU-27 will reach almost €20 billion with 60% of investments offshore [23]. Although the investment costs are considerably higher for offshore than for onshore wind farms, they are partly offset by a higher total electricity production from the turbines, due to higher offshore wind speeds.

Offshore wind turbine is still around 50% more expensive than onshore wind turbine. The higher offshore capital costs are due to the larger structures and complex logistics of installing the towers. The costs of offshore foundations, construction, installations and grid connection are significantly higher than onshore. For example, installing the entire offshore turbine is generally 20% more expensive and towers and foundations cost more than 2.5 times the price of a similar onshore project. Offshore costs depend largely on weather and wave conditions, water depth and distance from the coast [23].

Table 6 [23] gives information on some of the recently established offshore wind farms. As shown, the chosen turbine size for offshore wind farms ranges from 2 to 3.6 MW, with the newer wind farms being equipped with the larger turbines. The size of the wind farms also varies substantially, from the fairly small Samsø wind farm of 23 MW, to Neysted with a rated capacity of 165 MW. Investment costs per MW range from a low of 1.2 million €/MW (Middelgrunden) to 2.0 million €/MW (North Hoyle and Burbo Bank). As a result, the costs of future offshore farms may be different [23].

Although wind speeds generally increase with distance from shore, construction costs increase as well. The construction of offshore wind farms at locations further from the shore often implies placement in deeper waters and changed weather conditions. The overall cost increase of investment costs is indicated in Table 7 [25]. It shows that offshore investment cost might increase from 1800 to 2878 €/KW as the distance to the coast. Installation and grid connection costs are those most affected when offshore wind farms are located further from the shore. At larger distances installation costs increase because of the greater travelling time needed from the holding port to the site. In addition, weather conditions usually worsen further offshore making installation more difficult. Another cost affected when the distance to the shore increases is the export cable, which connects the wind farm to a suitable connection point on land. The factors influencing cable costs are cable size, sea bed conditions and the possible need for transformer stations [25].

A variety of meteorological and seabed conditions contribute to construction costs, including tidal currents, wind-driven currents, storm surges, extreme and breaking ocean waves, and soil conditions. In addition, water depth has a significant effect on construction and project costs [26]. The distance to the shore affects water depth. As one moves to deeper water the foundation costs of wind turbines tend to increase. Depth limitations for conventional foundations increase the appeal of alternative foundation technologies, such as floating structures. For offshore wind turbines with capacities between 1 and 1.5 MW the foundation costs are estimated to increase from €317,000 at 7 m depth to €352,000 at 16 m depth; a cost increase of 11%. Foundation supply costs can differ from 300,000 €/MW at 15 m to 1,000,000 €/MW at 40 m, using monopiles. Table 8 [25] presents the offshore installation costs as a function of water depth, based on the reference cost of 1800 €/KW in the shallowest waters.

In order to illustrate the economics of offshore wind turbines in more detail, the two largest Danish offshore wind farms can be taken as examples. The Horns Rev project, located approximately

Table 6
Key information on recent offshore wind farms [23].

	In operation	Number of turbines	Turbine size	Capacity (MW)	Investment costs € million	Investment costs million €/MW
Middelgrunden (DK)	2001	20	2	40	47	1.2
Horns Rev I (DK)	2002	80	2	160	272	1.7
Samsø (DK)	2003	10	2.3	23	30	1.3
North Hoyle (UK)	2003	30	2	60	121	2.0
Nysted (DK)	2003	72	2.3	165	248	1.5
Scroby Sands (UK)	2004	30	2	60	121	2.0
Kentish Flats (UK)	2005	30	3	90	159	1.8
Barrows (UK)	2006	30	3	90	–	–
Burbo Bank (UK)	2007	25	3.6	90	181	2.0
Lillgrunden (S)	2007	48	2.3	110	197	1.8

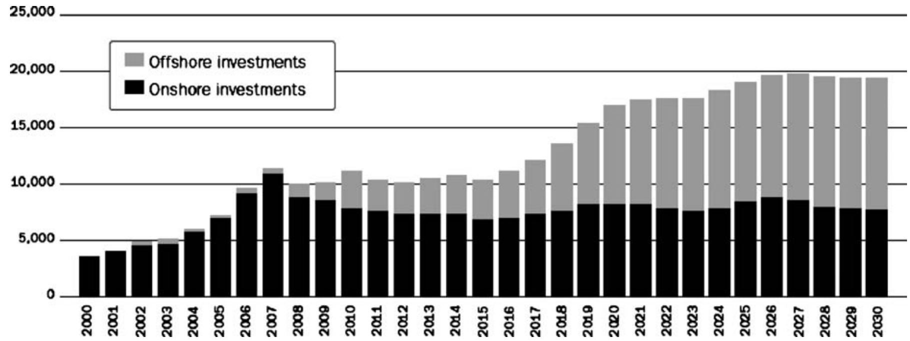

Fig. 7. Wind energy investments from 2000 to 2030 (€ mio) in the EU.

Table 7
Increase in offshore investment costs as function of distance to the coast (€/KW) [25].

	Distance to cost (km)							
	0–10	10–20	20–30	30–40	40–50	50–100	100–200	>200
Turbine	772	772	772	772	772	772	772	772
Foundation	352	352	352	352	352	352	352	352
Installation	465	476	476	500	511	607	816	964
Grid connection	133	159	159	211	236	314	507	702
Others	79	81	81	84	85	87	88	89
Total cost	1800	1839	1878	1918	1956	2131	2534	2878

Table 8
Increase in offshore investment costs as function of water depth (€/KW) [25].

	Water depth (m)			
	10–20	20–30	30–40	40–50
Turbine	772	772	772	772
Foundation	352	466	625	900
Installation	465	465	605	605
Grid connection	133	133	133	133
Others	79	85	92	105
Total cost	1800	1920	2227	2514

15 km off the west coast of Jutland (west of Esbjerg), was finished in 2002. It is equipped with 80 machines of 2 MW, and has a total capacity of 160 MW. The Nysted offshore wind farm is located south of the island of Lolland. It consists of 72 turbines of 2.3 MW and has a total capacity of 165 MW. Both wind farms have their own on-site transformer stations, which are connected to the high voltage grid at the coast through transmission cables. The farms are operated from onshore control stations, so staff is not required at the sites. The average investment costs related to these two farms are shown in Table 9 [23].

Consequently, the main differences in the cost structure between onshore and offshore turbines are linked to three issues: foundations are considerably more expensive for offshore turbines. Transformer stations and sea transmission cables increase costs. Installation cost increase both due to increasing distance to the coast and water depth.

Table 9
Average investment costs per MW related to offshore wind farms in Horns Rev and Nysted [23].

	Investments 1000 €/MW	Share (%)
Turbines ex works, including transport and erection	815	49
Transformer station and main cable to coast	270	16
Internal grid between turbines	85	5
Foundations	350	21
Design and project management	100	6
Environmental analysis	50	3
Miscellaneous	10	<1
Total	1680	100

6. Employment

It is impossible to manufacture, build, install and maintain wind turbines without people. It is equally impossible to plan, gain permits for and supervise a wind farm without them. Unsurprisingly then, employment related to wind energy has also gone up strikingly in recent years. Over the past 5 years, the EU wind energy industry has created more than 60,000 new jobs. On average, the wind energy sector in Europe has employed 33 new people every day, 7 days a week over the past 5 years [27].

From Table 10, it can be seen that wind turbine and component manufacturing employed some 64,000 directly and 43,000 indirectly in 2007. Wind farm development, installation, operations and maintenance employed 29,000 directly and an additional 15,000 were employed directly in other wind energy-related jobs. These figures do not take into account the higher employment effect of installing, operating and maintaining offshore wind turbines. The additional employment effect of including the higher cost (and higher employment per MW installed) of offshore capacity is estimated at 2800 jobs, taking the total employment from wind energy in the EU to 154,000 in 2007 [27].

As seen from Fig. 8, wind energy employment in the EU will more than double from 154,000 in 2007 to almost 330,000 in 2020. Onshore wind energy will continue to be the largest contributor to employment throughout the period. By 2025, offshore wind energy employment will exceed onshore employment. By 2030, more than 375,000 people will be employed in the European wind energy sector – 160,000 onshore and 215,000 offshore [27].

The wind sector worldwide has become a major job generator: within only 3 years, the wind sector worldwide almost doubled the number of jobs from 235,000 in 2005 to 440,000 in the year 2008. These 440,000 employees in the wind sector worldwide, most of them highly skilled jobs, are contributing to the generation of 260 TWh of electricity [28].

Table 10
Direct and indirect employment by type of company.

Company	Share of direct employment (%)	Direct employment	Indirect employment	Total
Wind turbine (WT) manufacturing	37	40,182.8	42,716.0	
Component manufacture	22	23,892.0		
Wind farm development	16	17,376.0	–	
Installation, operation and maintenance	11	11,946.0	–	
IPP/utilities	9	9774.0	–	
Consultants	3	3258.0	–	
R&D/universities	1	1086.0	–	
Financial	0.3	325.8	–	
Others	0.7	760.2	–	
Total	100	108,600.0	42,716.0	151,316.0

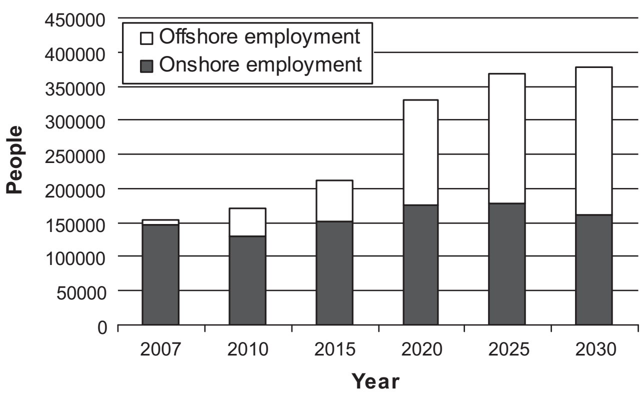

Fig. 8. Wind energy sector employment in the EU.

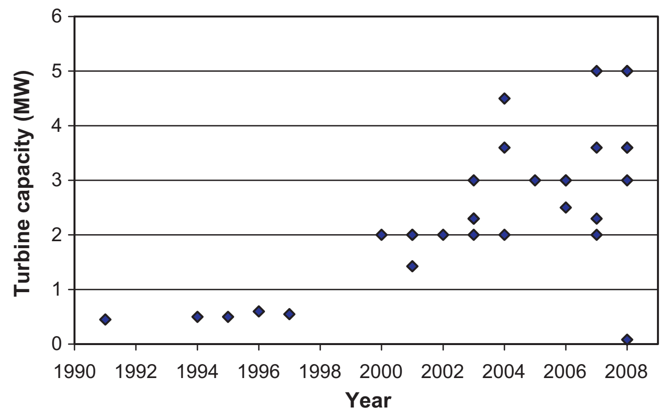

Fig. 10. Increasing turbine capacity of European offshore wind farms over time.

7. Industry and installation

A wind power system is a sophisticated combination of components and sub-systems that have to be designed in an interdisciplinary and integrated manner. In addition, the size and complexity of wind turbines is increasing rapidly over time, as seen in Fig. 9 [27]. Wind energy technology itself also moved very fast towards new dimensions. At the end of 1982, a 55 kW wind turbine with a 15 m rotor diameter was state-of-the-art. Today, 5000 kW turbines with a rotor diameter of around 126 m are available from many manufacturers [3,29].

The turbine capacity used in both onshore and offshore wind farms has increased over the past decade. Larger turbines are thought to allow for lower operation and maintenance costs, installation and foundation costs per unit of capacity [16]. Currently, offshore installations only constitute a very small part of the wind turbine market, but offshore wind is set to develop in a significant way and the potential offshore market is the main driver for large turbine technology development. Most offshore installations use large-scale versions of the same architecture as onshore turbine designs. This basic offshore configuration includes a three-bladed, pitch-controlled, upwind horizontal-axis turbine with a rotor, drivetrain, and other systems that are larger than their typical onshore counterparts [26]. Offshore wind turbines are also greater than onshore turbines. A typical onshore turbine installed today has a tower height of about 60–80 m, and blades about 30–40 m long; most offshore wind turbines are at the top end of this range. Increasing turbine capacity and hub height of European offshore wind farms are presented in Figs. 10 and 11, respectively. Offshore tur-

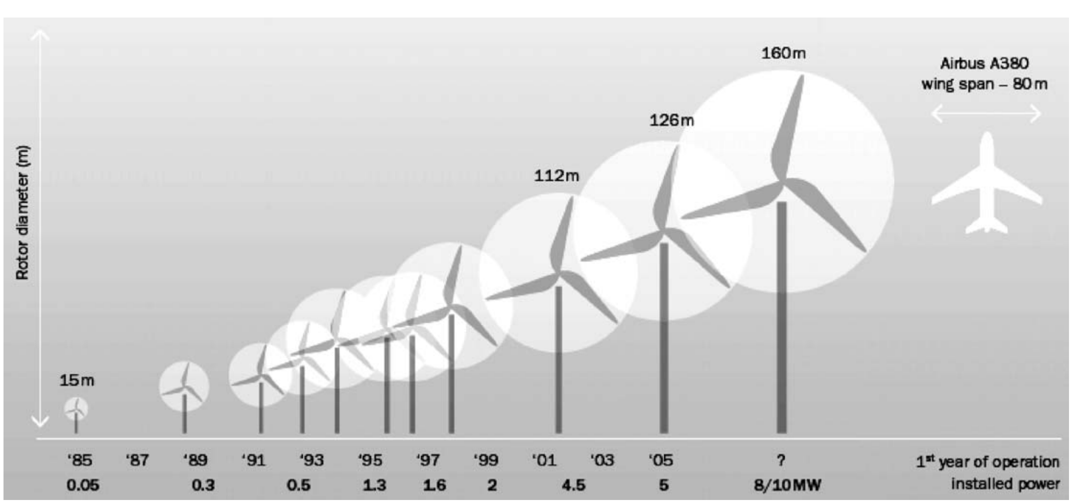

Fig. 9. Size evolution of wind turbines over time.

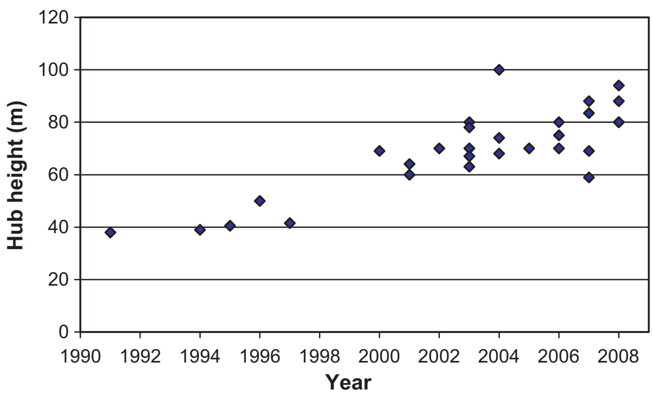

Fig. 11. Increasing hub height of European offshore wind farms over time.

bines installed today are generally between 2 and 4 MW [1]. But, the largest turbines used so far have been 5 MW built by REPower and were used in Beatrice and Thornton Bank. However, Enercon has installed a land based 6 MW turbine and Clipper Windpower is planning on building a 10 MW turbine [16].

The offshore wind industry is likely to develop along the path illustrated in Fig. 12. The offshore area has been divided into different classes depending on the distance from the coastline, specifically areas less than 10 km from the coast, areas 10–30 km away, areas 30–60 km away and areas more than 60 km away. Wind turbines have generally been built in relatively shallow water, less than 30 m in depth [25]. For offshore environments, gravity foundation/tube tower and monopile designs are considered appropriate for water depths up to 30 m. Stiffer, multi-pile configurations with broader bases suitable for development, including tripods, jackets, mono-towers and jackets, and suction bucket support structures are envisioned for water depths up to 60 m or greater [26]. Foundation design is one specific area where the opportunity to leverage existing expertise from ocean engineering, specifically from the oil and gas industry should be taken advantage of. Although multi-pile foundations may be viable in water depths up to and above 60 m, floating turbine structures may become necessary in much deeper waters. These structures would be secured to the ocean floor via catenary guy wires, mooring lines, or taut tension legs, which in turn would be fastened to anchors or gravity-based platforms [26].

Structures to support wind turbines come in various shapes and sizes, the most common illustrated in Table 11. Monopiles have been chosen for most of the installed offshore wind farms to date. Concrete gravity base structures have also been used on several projects. As wind turbines get larger, and are located in deeper

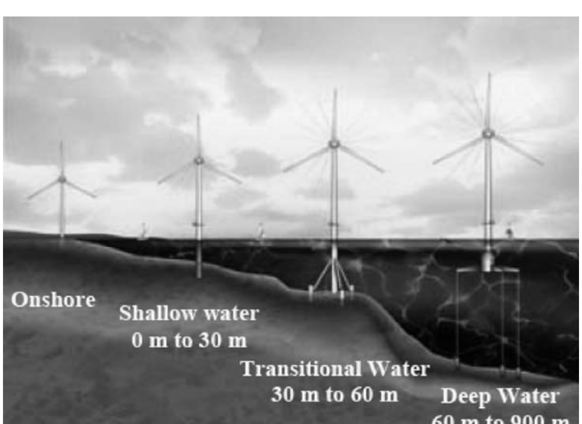

Fig. 12. Technology progression for offshore wind turbines.

Table 11
Support structure options.

Structure	Use	Examples
Monopile	Sallow to medium water depths	Horns Rev, Samsø, Frederikshavn, Arklow Bank, Lely, Egmong ann Zee, Prinses Amalia, Bockstigen, Utgrunden, Yttre Stengrund, North Hoyle, Scroby Sands, Kentish flats, Barrow, Burbo Bank, Inner Dowsing, Lynn
Gravity base	Sallow to medium water depths	Thornton Bank, Vindeby, Middelgrunden, Nysted, Lillgrund
Jacket	Medium to deep water depths	Beatrice
Tripod	Medium to deep water depths	Hooksiel
Floating structures	Very deep water depths	Birindisi

water, tripod or jacket structures may become more attractive [30]. The deepest offshore turbines constructed to date have been at Beatrice where turbines were constructed on jacketed foundations in 45 m of water. Excluding Beatrice, the deepest offshore wind farms have been built in water only 10–20 m deep, due largely to the constraints of monopole and gravity foundations. Floating wind turbines are being tested by Blue H in Italy which would allow for development in water over 100 m deep [16].Offshore turbines have technical needs not required of onshore turbines due to the more demanding climatic environmental exposure offshore. Offshore turbines look similar to those onshore with several design modifications. These include strengthening the tower to cope with wind–wave interactions, protecting the nacelle components from sea air, and adding brightly colored access platforms for navigation and maintenance [1]. Undersea collection cables connect multiple turbines in the wind facility and transport the electricity from them to a transformer where the combined electricity is converted to a high voltage for transmission via undersea cables to a substation. There, the electricity is connected to the onshore electricity grid. Alternative approaches, such as using the wind to produce hydrogen (through the hydrolysis of desalinated seawater), which would be shipped to shore for later use, are also being investigated [1].

8. Conclusions

Europe is an energy intensive continent, which relies heavily on imported fuels, and it is faced with the global challenges of climate change, depleting indigenous energy resources, increasing fuel costs and the threat of supply disruptions. For this reason, Europe must use the opportunity created by the large turnover in capacity to construct a new, modern power system capable of meeting the energy. In recent years, wind energy has become a valuable and dependable source of electricity worldwide. Over the past decade, the global market for wind power has been expanding faster than any other renewable energy source.

Wind energy also creates benefits in terms of employment, investment, research and economic activity in the electricity sector. Today, Europe leads the world in terms of the manufacturing and development of wind energy technology. For this reason, wind power is vital for Europe's future. At present, nearly 4% of the EU's electricity consumption is met by wind power, but this share could increase to almost one quarter by 2030, provided that the right framework is introduced and current distortions in the EU energy markets are removed. In Europe, the vast majority of wind power

is generated from onshore wind farms. However, the wind power sector has begun to move offshore in recent years.

Offshore wind energy is indeed a very promising field. It has been discussed briefly and has been found to have some advantages over its onshore counterpart. Several offshore wind farms have been developed in Europe. By the end of 2008, 1471 MW of offshore wind turbines are in operation in the EU. This rate is nearly 2.23% of the EU's total installed wind power capacity. In addition, in 2030, the 150 GW of installed capacity will be able to produce 563 TWh of electricity, equal to between 12.8% and 16.7% of EU electricity consumption, depending on the development in demand for power. Approximately half of Europe's wind electricity would be produced offshore in 2030. An additional 592 TWh will be produced onshore, bringing wind energy's total share to between 26.2% and 34.3% of EU electricity demand. But the technology is still at an early stage. This has led to the need for a new combination of research areas.

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